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LITHIUM EMITTER HEATPIPE RESEARCH AT PHILLIPS LABORATORY POWER AND THERMAL MANAGEMENT DIVISION

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Final Report

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13. Supplementary Notes

14. Abstract The purpose of the Li-EHP test was to experimentally demonstrate whether or not the Li-EHP is capable of creating uniform temperature conditions on the emitter surface of a THPM. To do so required the fabrication of a suitable vacuum system, a vacuum furnace which was capable of producing sufficiently high temperature (1800-200K) to initiate heat pipe action, and a means of acquiring extremely high temperature data. Instrumentation was selected which would enable the experimenters to measure the temperature at several locations on the exterior of the Li-EHP so that temperature differentials could be obtained which would indicate performance of the heat pipe. In addition, the same tests performed on the Li-EHP were also performed on a molybdenum tube of approximately the same dimensions as the Li-EHP. Ultimately, Phillips Lab, sought to simulate extremely non-uniform heat source conditions as a strenuous test of the Li-EHP capabilities.

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KAFB	Kirtland Air Force Base
CVD	Chemical Vapor Deposited
DAS	Data Acquisition System
EHP	Emitter Heat Pipe
LiEHP	Lithium Emitter Heat Pipe
ORION	ORION International Technologies, Inc.
PL/VTP	Phillips Laboratory/VTP
TFE	Thermionic Fuel Element
THPM	Thermionic Heat Pipe Module
TI	Thermionic
W	Tungsten

LITHIUM EMITTER HEAT PIPE PERFORMANCE EVALUATION TEST PROGRAM

1. INTRODUCTION

1.1 BACKGROUND

The Phillips Laboratory Power and Thermal Management Division (PL/VTP) is currently investigating new methods and technologies for creating advanced power concepts for space applications. These investigations are being conducted at the PL/VTP Space Power Laboratory located at Kirtland Air Force Base (KAFB), New Mexico. As part of this research, PL/VTP, in conjunction with ORION International Technologies Inc. (ORION), has assessed thermionic (TI) conversion technology as a means of converting heat energy into electricity. Thermionic energy conversion systems boast relatively high conversion efficiency and high temperature operation. For these reasons they have been identified as suitable for use in space nuclear power systems. The majority of US and Russian research and development of TI converters has focused on the use of the Thermionic Fuel Element (TFE). This design concept has led to several problems associated with fuel swelling, fission gas production, and fission gas migration. One method of removing these problems is to de-couple the TI converter from the nuclear core design. This is the heart of the Thermionic Heat Pipe Module (THPM) concept, developed by Idaho National Engineering Laboratory and Thermacore, Inc.

A key element of the THPM, and one potential advantage over TFE systems is the use of an emitter heat pipe (EHP) assembly to achieve an isothermal emitter surface. This would enhance converter performance, and could be accomplished without excessive tailoring of fuel loads throughout the reactor core. The Lithium-EHP (Li-EHP) permits the THPM to be used in systems which display non-uniformity in the heat source, whether the heat source is solar thermal, combustion derived, or a nuclear reactor core. PL/VTP has undertaken the task to verify the ability of the Li-EHP to produce conditions on the emitter which enhance its performance.

1.2 PURPOSE

The purpose of the Li-EHP test was to experimentally demonstrate whether or not the Li-EHP is capable of creating uniform temperature conditions on the emitter surface of a THPM. To do so required the fabrication of a suitable vacuum system, a vacuum furnace which was capable of producing sufficiently high temperature (1800-200 K) to initiate heat pipe action, and a means of acquiring extremely high temperature data. Instrumentation was selected which would enable the experimenters to measure the temperature at several locations on the exterior of the Li-EHP so that temperature differentials could be obtained which would indicate performance of the heat pipe. In addition, the same tests performed on the Li-EHP were also performed on a molybdenum tube of approximately the same dimensions as the Li-EHP. Ultimately, PL sought to simulate extremely non-uniform heat source conditions as a strenuous test of the Li-EHP capabilities.

2. PROJECT/TEST DESCRIPTION

To test the annular heat pipe design, an EHP with no collector assembly was used. This heat pipe was constructed of Chemical Vapor Deposited (CVD) molybdenum, and filled with lithium. The Li-EHP was designed and fabricated by Thermacore, Inc., Lancaster, PA. Figure 1 is a schematic of a THPM showing the Li-EHP.

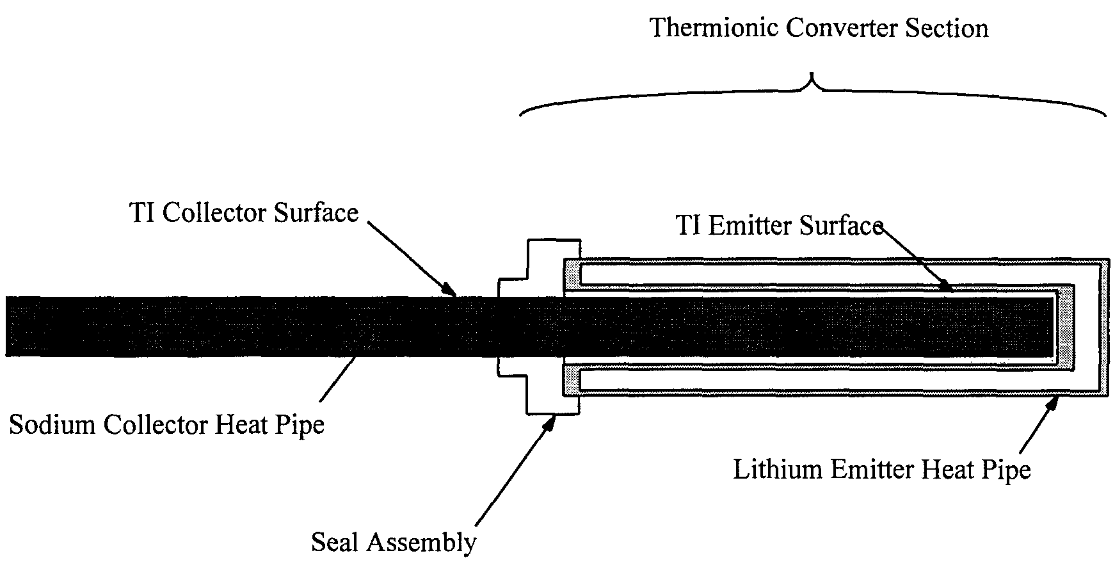

Figure 1. Schematic of THPM Showing Li-EHP.

The inner wall of the Li-EHP is 1.28 cm in diameter, the outer wall is 2.22 cm in diameter. The walls themselves are 0.11 cm thick and the gap between the walls, into which 20 g of lithium are loaded, is 0.2 cm. The device is 25.4 cm in length.

The interior surface of the Li-EHP forms the emitter surface of the THPM. The more uniform the temperature on the emitter surface the higher the efficiency of the conversion. Heat from a source which surrounds the exterior of the Li-EHP ignites the heat pipe action and, in theory, creates a highly uniform emitter surface temperature. In addition, the heat pipe action is intended to create uniform conditions on the emitter surface even if the heat source surrounding the Li-EHP is not itself uniform.

Several support systems were designed and fabricated for the Li-EHP tests including vacuum, heating/cooling, data acquisition, instrumentation and power systems. These systems were designed with a goal of full THPM testing.

2.1 VACUUM SYSTEM

The THPM and the Li-EHP were designed and constructed to perform in vacuum. At the temperatures required to test the Li-EHP, severe oxidation of the Li-EHP surfaces would rapidly degrade the performance of the device as well as potentially cause failure of the integrity of the lithium metal containment creating potentially unsafe conditions should the lithium be exposed to ambient conditions. Therefore, air testing, or even inert gas testing of the device was rejected and a vacuum system was designed to house the vacuum furnace and the test article. The added advantage of vacuum testing is it simulates the purely radiative heating environment of space.

Figure 2 shows the vacuum system used to test the Li-EHP. The vacuum system consisted of a 42 x 76 cm Pyrex glass bell jar which rests on an eight port feedthrough collar. The feedthrough collar, in turn, is supported by a modified MDC Corporation BP-18 baseplate. The BP-18 was modified so that it has 12 additional feedthrough ports to allow the introduction of electrical power and cooling water to the vacuum furnace and to extract data signals generated by temperature probes. The feedthrough ports on both the collar and the baseplate were 2.7 inch Conflat® fittings which use knife edge surfaces against a copper gasket to create the vacuum seal.

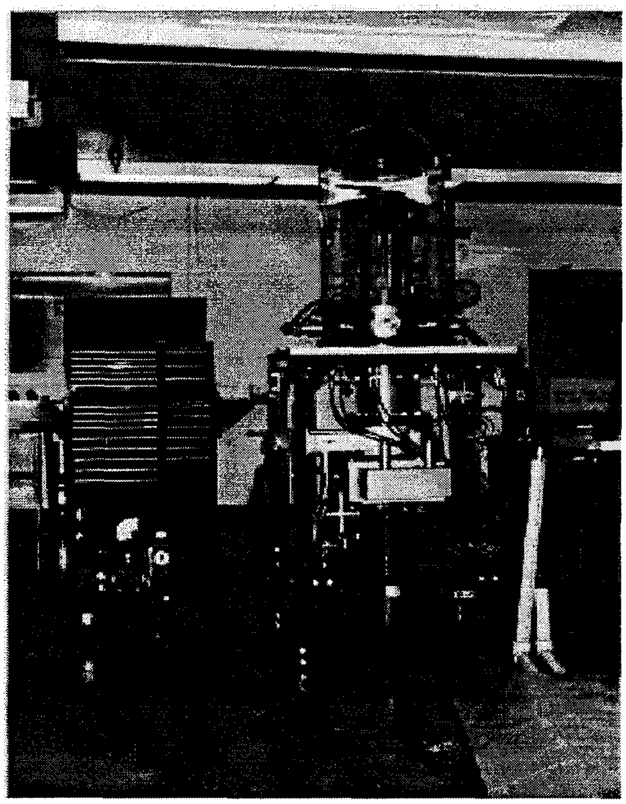

Figure 2. Photograph of Bell Jar Vacuum System.

The vacuum is created by a 6 inch inner aperture diffusion pump with a liquid nitrogen trap system. This arrangement allows for vacuums of ~1.2×10^{-6} torr *during* operation of the filament heaters. The diffusion pump was a CVC PMCS-6B pump which required a chiller water supply. An 80 kW HX-1000 Neslab chiller unit was acquired to perform the diffusion pump cooling and provide for all other cooling needs in the experiment. A 6 inch inner aperture gate valve and independently valved roughing lines allow the diffusion pump to operate even while the bell jar is open. The bell jar can be roughed down separately in a matter of minutes, and because the diffusion pump is running, the experimental apparatus can be evacuated to

1 x 10^{-6} torr within thirty minutes. The roughing pump is a 1800 CFM Sargent-Welch vacuum pump.

Thermocouple gauges were used to measure vacuum pressures between atmospheric and 1 x 10^{-4} torr. Ionization gauges were used to measure the vacuum pressures to 1 x 10^{-8} torr. A JC Controls vacuum gauge/ionization gauge controller was used to obtain vacuum pressure measurements. The JC Controls unit is outfitted with an RS232 data port so that vacuum pressure readings can be acquired by a computerized data acquisition system (DAS).

2.2 VACUUM FURNACE

The hot zone, which is capable of reaching temperatures higher than 2000 K, was contained within a furnace made of overlapping Tungsten (W) shields surrounded by a water-cooled copper jacket as shown in Figure 3. The furnace was designed to allow heating by vertically mounted Tungsten wire-mesh heaters. Three heaters were spaced around the furnace, and are capable of independent operation, allowing for varied circumferential temperature profiles. This test series consisted of applying a thermal load to the Li-EHP from only one of the strip heaters.

The hot zone consists of six concentric, overlapping tungsten shields surrounded by a water cooled copper jacket as shown in Figure 3. The shields come apart in three separate "clamshell" sections. This arrangement allowed for easy individual assembly of each sub-unit. In theory, this also allowed for individual installation and alignment of the filaments. However, because of the difficulty in working tungsten, the radius of curvature of the shields was not precise. This made assembly of the unit difficult; therefore, the hot zone was rarely disassembled.

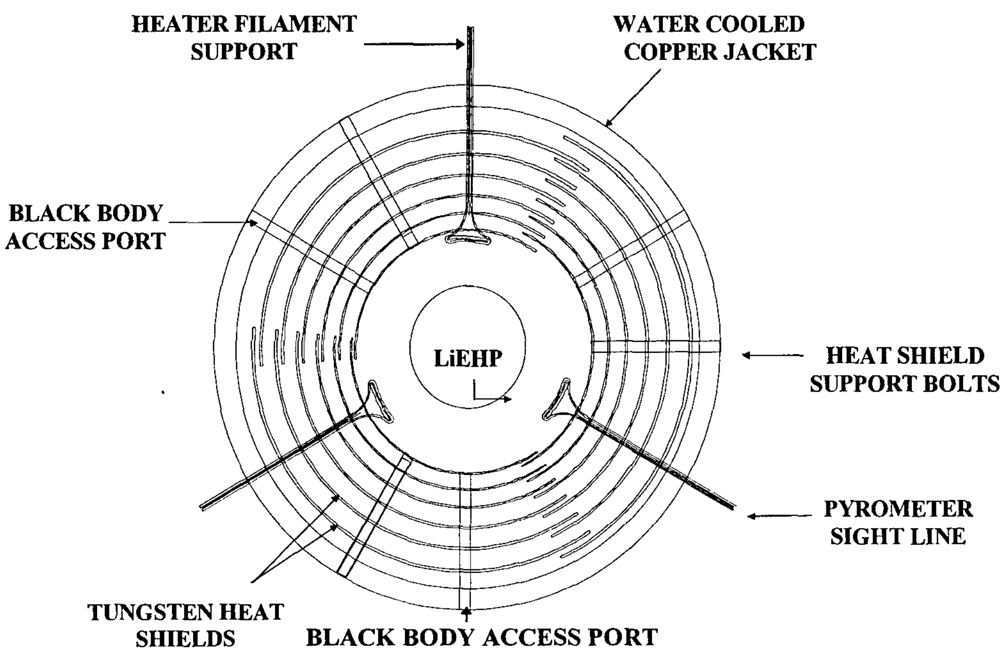

Figure 3. Top View of Vacuum Furnace with Tungsten Shields.

The filaments are made from a tungsten mesh, with 0.08 cm thick tungsten strips used as filament leads. The filaments are very low resistance, but their resistance varies greatly with temperature. This requires a very high current, low voltage power supply to energize the filaments. The filament draws 230 A at 12 V if configured with ~ 5 m of 000 American Wire Gauge power leads to and from the filament. This results in a filament temperature of 2100 K in this test configuration. A maximum lifetime or temperature for the filament was not established as failure was not encountered. The operational time limitations of the high temperature vacuum furnace were dependent on the behavior of the vacuum, not on any apparent filament or power supply limitation.

The resistance of the filament varies greatly with temperature. The filament resistance versus temperature is shown in Figure 4. The change in resistance with temperature can greatly change the load. An EMI 20 V, 500 A power supply was used to heat the filament. With this power supply in voltage limiting mode the filament temperature was stable to within less than one degree once the system had thermally stabilized.

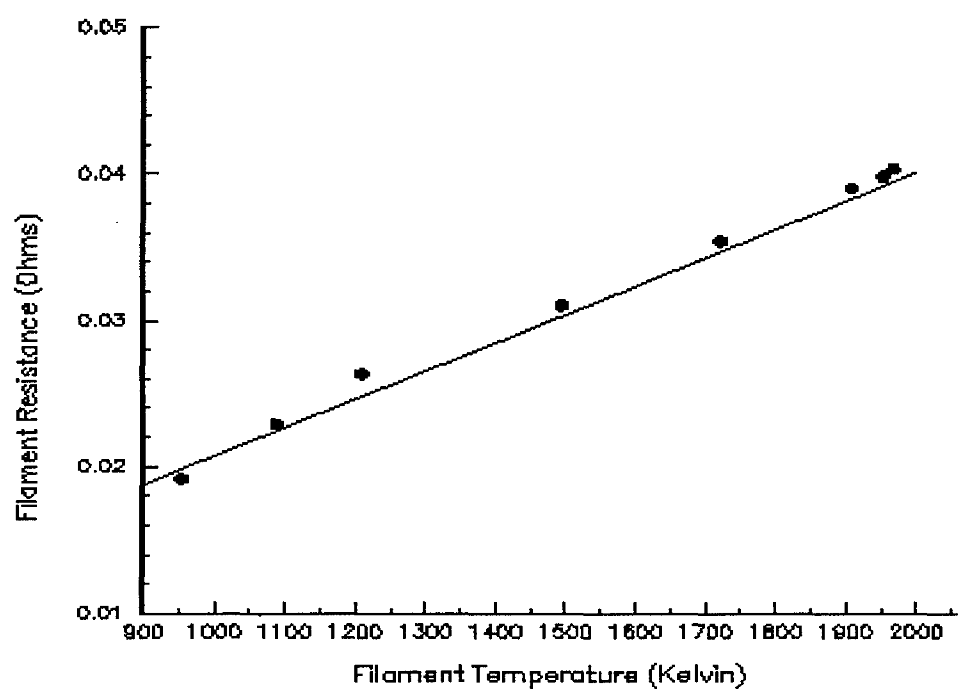

Figure 4. Filament Resistance Versus Filament Temperature.

Large heat losses require excessive amounts of electrical power for the filament, and lead to high temperatures inside the vacuum chamber. Therefore, the hot zone was designed to contain the heat of the filament. This containment fixture allows temperatures in excess of 2000 K in the hot zone, while keeping the vacuum system at room temperature. Viton seals fail at temperatures of greater than 150 ^{o}C. In the absence of active cooling on the exterior of the hot zone, the chamber walls would soon reach a temperature almost equal to the interior temperature. The water cooling removes the heat escaping from the hot zone. This allows the use of ordinary materials in the vacuum system. The low temperatures of the vacuum system also reduce the problems associated with the outgassing of surfaces. In early tests of the hot zone, the water-cooled, copper jacket changed temperature by only ~5 K for an electrical input power of 2000 W.

Calculations of the effectiveness of a six shield assembly in containing heat are shown in Figure 5. The calculations were performed assuming all the heat energy passed through the sides of the shields, none through the top and bottom, and a uniform power distribution impinged on the inner most shield.

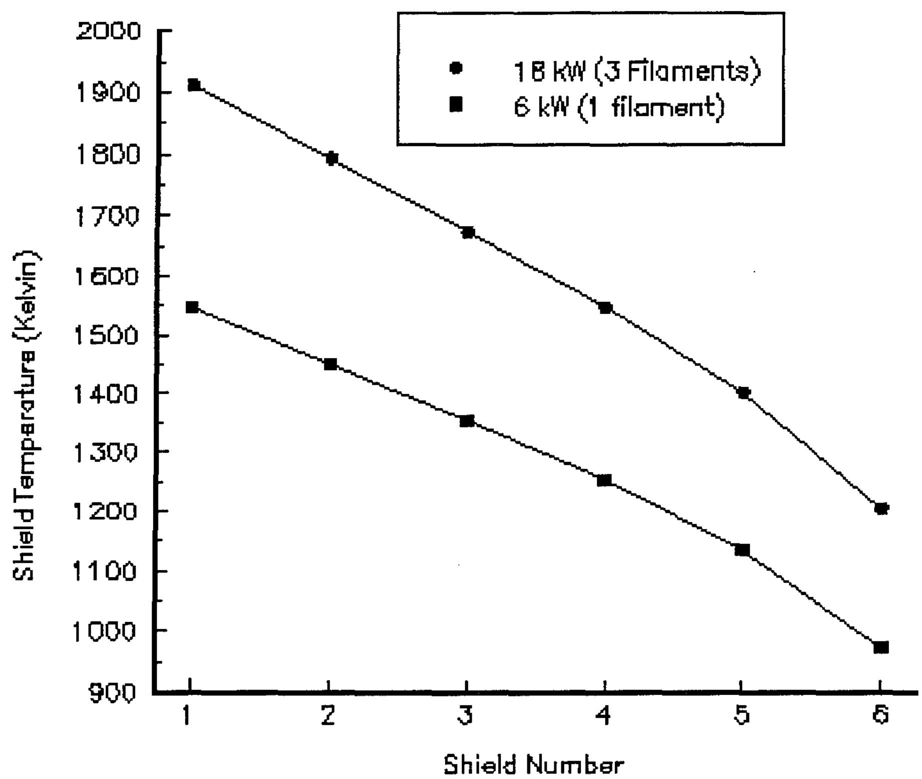

Figure 5. Hot Zone temperature profile.

These calculations indicate that ~11% of the interior heat energy escapes the system through the outer most shield.

2.3 INSTRUMENTATION

The emitter exterior surface was monitored using black body optical fiber probes, sapphire light pipes, and tungsten-rhenium thermocouples. The interior surface was instrumented with K-type thermocouple probes. Both circumferential and axial profiles were developed. As a baseline for comparing heat pipe behavior, the same test series was run using a molybdenum tube of similar exterior dimensions. The test geometry/instrumentation map is shown in Figure 6.

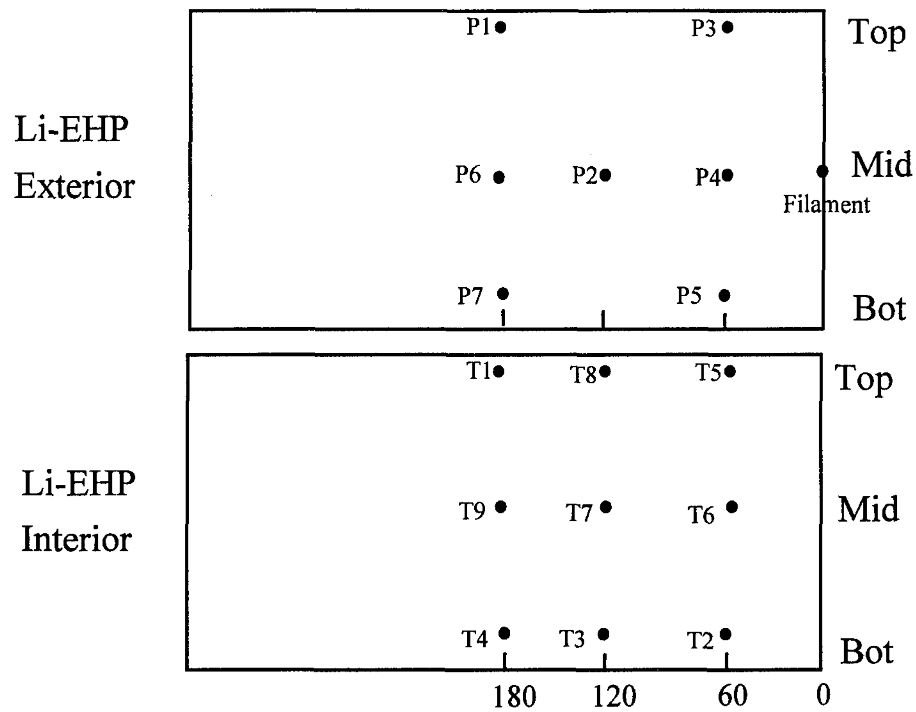

Figure 6. Instrumentation Map on Expanded Li-EHP.

The high temperatures of the hot zone created difficulties in monitoring the experiment. The closed nature of the hot zone limits the access to the region. The high temperatures limit the measurement options to pyrometry, pyrometry based methods, or tungsten-rhenium thermocouples. Twelve 0.3 cm diameter access holes were drilled in the hot zone walls to provide opportunities for data acquisition. The twelve ports allow access to the interior of the hot zone, and the small size of the ports limits the amount of heat leakage.

The points labeled P1 - P7 were instrumented with black body probes and/or C-Type thermocouples. The C-Type thermocouples were constructed from 0.01 cm rhenium-doped tungsten wire, which was inserted through an alumina insulation sheath 0.15 cm in diameter. These rigid alumina sheaths could be inserted into the same holes used to accommodate the blackbody and pyrometry probes. The points labeled T1 - T9 were K-type thermocouples mounted to the interior of the Li-EHP.

The instruments selected for the most accurate data acquisition to be used in the hot zone were optical pyrometer based probes. The probes, manufactured by Accufiber, Inc., consist of a sapphire rod attached to an optical fiber lead. The probes come in two varieties: pyrometer and blackbody. The pyrometer probe is a non-contact instrument. It captures light emitted from a source, and determines the object's temperature by using the Planck blackbody relationship. The blackbody probe is identical in construction with the pyrometer probe, except for a thin film of platinum deposited on the tip. The tip touches the hot surface in question. The hot surface causes the platinum tip to glow. The platinum tip on the blackbody probes make the calibration of the device straightforward. The emissivity of platinum as a function of temperature is programmed into the probe controller. The pyrometer can be pointed at any type of surface; however, the emissivity of the surface must be provided to the controller. The emissivity of tungsten is a function of temperature. The controller accommodates up to a second order function to allow a temperature dependent emissivity to be used. The function used (shown in Figure 7) was obtained from the National Bureau of Standards. The least squares fit to the data is given by:

$$\varepsilon = 2.6104 \times 10^{-2} + 1.1367 \times 10^{-4}\, T_C + 1.4750 \times 10^{-8}\, T_C^2$$

where temperature, T_C, is provided in Celsius. The Accufiber pyrometer reader was set to take readings in Celsius, hence the use of the above formula.

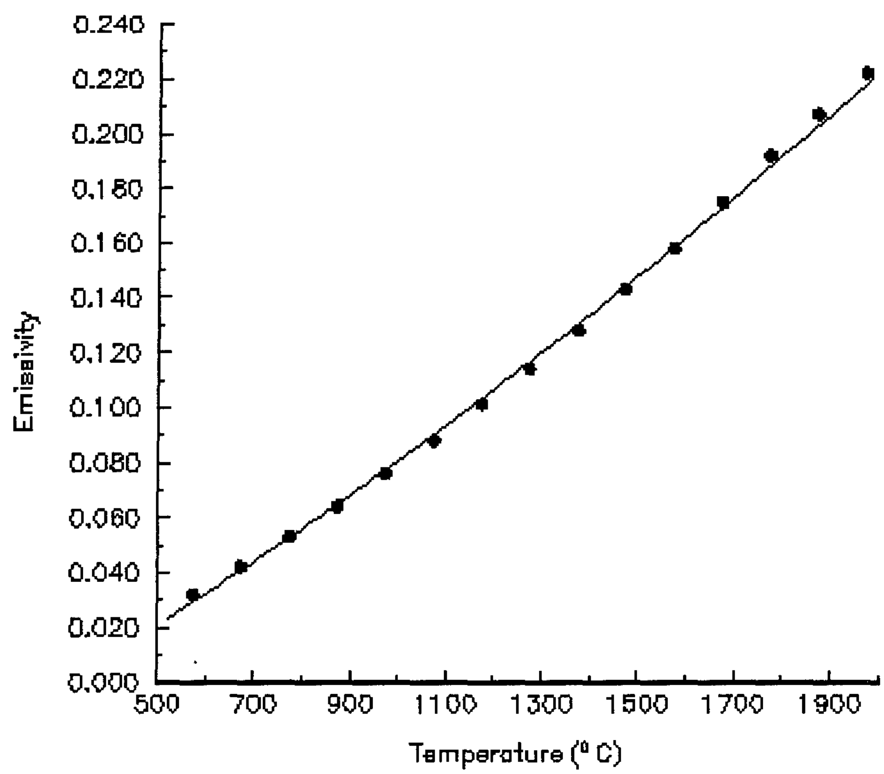

Figure 7. Tungsten emissivity as a function of temperature.

Data was obtained using a computerized DAS consisting of a Gateway 2000, 80486 Intel Processor, 66 MHz system. An American Data Acquisition Corporation 5305EN, 12 bit Analog-to-Digital (A/D) System was used to acquire the Accufiber blackbody and pyrometer data, tungsten-rhenium (C-Type) thermocouple data and chromel-alumel (K-Type) thermocouple data.

The system included a 5020MF A/D converter card and three 4000TCEX thermocouple interface cards. As many as 16 K-Type thermocouples, 16 C-Type thermocouples, 16 user defined type thermocouples, 2 blackbody probes, one light pipe, up to 10 analog input signals (such as the filament current and voltage for this test), and vacuum pressure data could be acquired with this system.

3. RESULTS

From the Li-EHP series of tests, data was collected for the device (molybdenum tube or emitter heatpipe) temperature versus filament temperature, and the temperature distributions of the seven exterior and nine interior points were obtained. The temperature differences between interior and exterior were calculated, and the temperature differences between vertical and horizontal points were plotted against a common point of reference (P3 in Figure 6).

The temperature difference between P4 and P2 is shown in Figure 8 for both the emitter heat pipe and the molybdenum tube. The molybdenum tube shows behavior which is consistent with heat conduction along its surface and radiative heat loss. The emitter heat pipe shows behavior which is similar to that of the molybdenum tube for surface temperatures less than ~1100 K. The behavior of the Li-EHP at lower temperature (700 - 1100 K) is characterized by a slowly increasing temperature difference. The temperature at which heat pipe action became apparent varied between 1100 K to 1400 K (P4 temperature), however, it is clearly marked by a drop in temperature difference. Upon initiation of heat pipe action, the respective temperature difference rapidly changed and assumed a value which was independent of temperature.

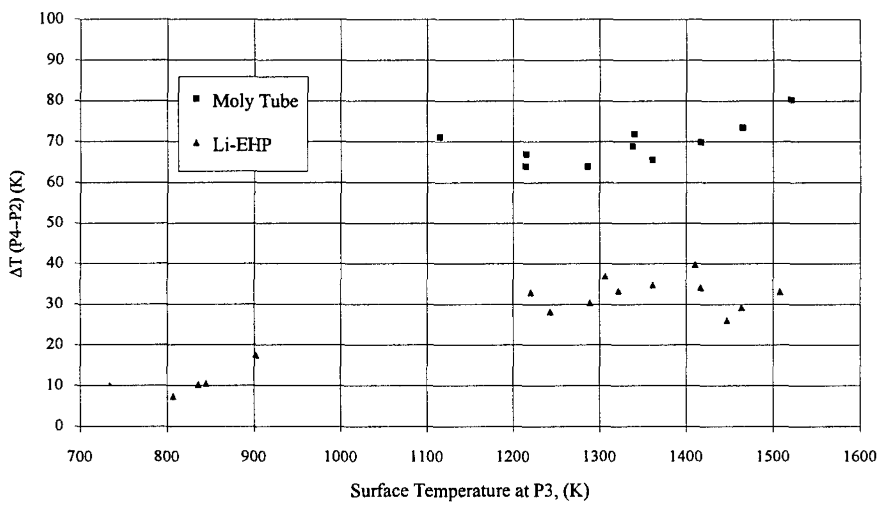

Figure 8. Comparison of Molybdenum Tube to Emitter Heatpipe, Circumferential.

The temperature difference from P4 to P3, the axial profile, is presented in Figure 9. The axial profile for both the molybdenum tube and Li-EHP are roughly the same until heat pipe action begins. After heat pipe action began, the difference on the Li-EHP drops to below 5 K. The unusual fact that the ΔT is better at temperatures below the onset of heat pipe action, especially circumferentially, is possibly due to the double wall structure of the Li-EHP; the inner wall acts as a heat shield, retarding heat losses from the exterior wall and elevating the temperatures along the entirety of the exterior.

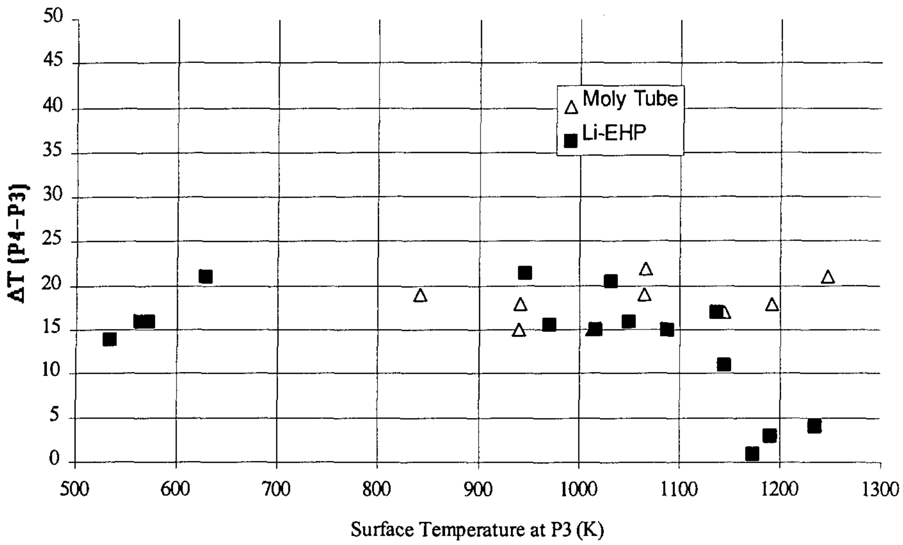

Figure 9. Comparison of Molybdenum Tube & Emitter Heatpipe, Axial.

Before and after the onset of heat pipe action, the temperature difference between points on the interior (Figure 10) displayed similar behavior to that shown previously in Figure 8 for the exterior. A gradual rise in ΔT followed by a marked decrease in ΔT indicates heat pipe action at approximately 1350 K.

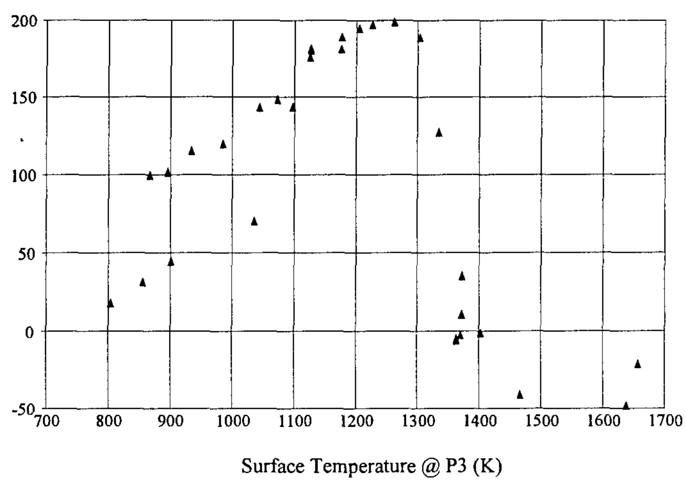

Figure 10. Interior Temperature Differences.

The temperature difference between corresponding points on the interior and exterior of the heat pipe revealed somewhat unusual behavior. The temperature difference dropped sharply at a reference point temperature (P3) of ~1000 K, indicating the onset of localized heat pipe action radially inward before heat pipe action circumferentially and axially (Figure 11). The behavior was repeatable as revealed in data from two separate heatings of Li-EHP.

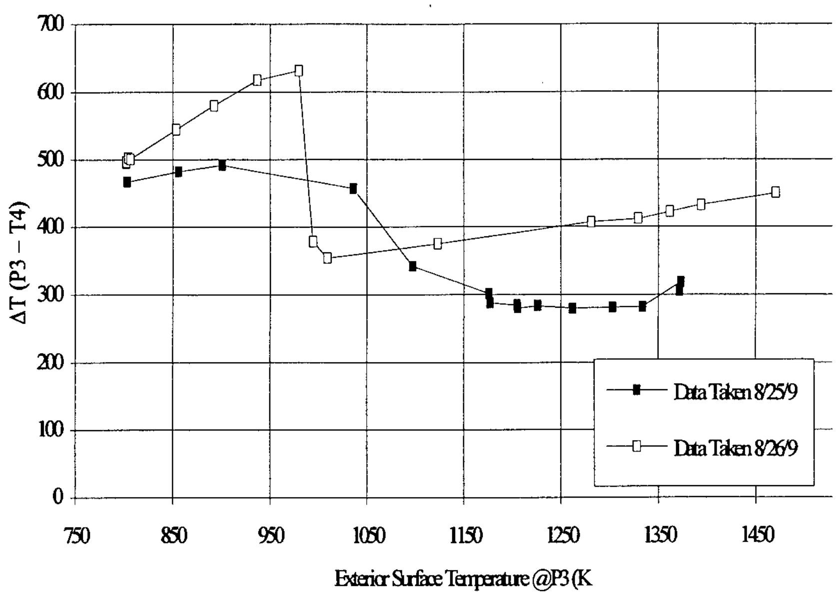

Figure 11. Temperature Difference Between Interior and Exterior Points.

4. POTENTIAL APPLICATIONS

These results indicate that heat pipe action is present in the annular emitter heat pipe. The emitter heat pipe exhibited the desired performance from center to top and bottom, with a temperature spread of less than 10 K along the exterior of the device. The circumferential temperature differences were much larger.. These large temperature differences will limit the performance of the power producing THPM when heated by a non-uniform heat source. This limits the potential application of the annular Li-EHP. The temperature differences along the THPM surface with two heaters should be similar to that between P2 and P4. However, a two heater operation should provide maximum surface temperature differences of on the order of 30 K.

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